

# Physics at an Upgraded Fermilab Proton Driver

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In 2004 the Fermilab Long Range Planning Committee identified a new high intensity Proton Driver as an attractive option for the future, primarily motivated by the recent exciting developments in neutrino physics. Over the last few months a physics study has developed the physics case for the Fermilab Proton Driver. The potential physics opportunities are discussed.

## 1. INTRODUCTION

In the last few years there has been interest in a new generation of high intensity multi-GeV proton accelerators. At Fermilab the design that is currently favored [1–3] consists of an 8 GeV  $H^-$  superconducting (SC) Linac that utilizes International Linear Collider (ILC) technology. The Linac would produce a 0.5 megawatt beam which could be upgraded to 2 megawatts. A small fraction of the 8 GeV beam would be used to fill the Fermilab Main Injector (MI) with the maximum number of protons that, with some modest improvements, it can accelerate. This would yield a 2 megawatt MI beam at an energy anywhere within the range 40 GeV to 120 GeV.

Hence the upgraded proton source would simultaneously deliver two beams: a 2 megawatt beam at MI energies, and an  $\sim 0.5 - 2$  megawatt beam at 8 GeV. To illustrate this the cycle structure is shown in Fig. 1. The MI would receive one pulse from the Linac every 1.5 sec. Note that the MI fill time is very short ( $< 1$  ms). The MI cycle time is dominated by the time to ramp up to 120 GeV and ramp down to 8 GeV. The 14 Linac pulses that are available, while the MI is ramping and at flat top, would provide beam for an 8 GeV program. Improvements in the MI ramping time might eventually enable more of the 8 GeV Linac beam to be accelerated in the MI, yielding beam

powers exceeding 2 megawatts.

## 2. MOTIVATION

The interest in a new Fermilab Proton Driver is motivated by the exciting discoveries that have been made in the neutrino sector. In the last few years solar, atmospheric, and reactor neutrino experiments have revolutionized our understanding of the nature of neutrinos. We now know that neutrinos produced in a given flavor eigenstate can transform themselves into neutrinos of

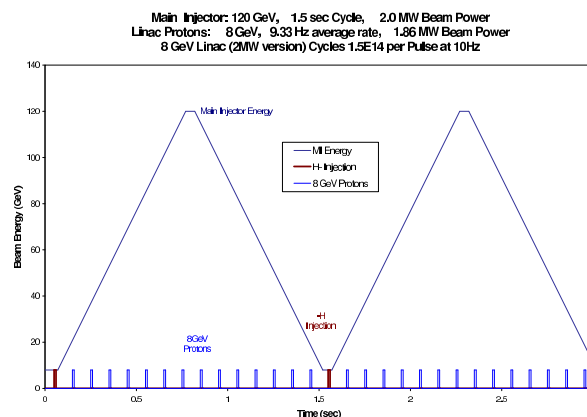


Figure 1. Proton Driver bunch structure and the Main Injector cycle.

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a different flavor as they propagate over macroscopic distances. This means that, like quarks, neutrinos have a non-zero mass, the flavor eigenstates are different from the mass eigenstates, and hence neutrinos mix. However, we have incomplete knowledge of the properties of neutrinos since *we do not know the spectrum of neutrino masses, and we have only partial knowledge of the mixing among the three known neutrino flavor eigenstates*. Furthermore, it is possible that the simplest three-flavor mixing scheme is not the whole story, and that a complete understanding of neutrino properties will require a more complicated framework. In addition to determining the parameters that describe the neutrino sector, the three-flavor mixing framework must be tested.

The discovery that neutrinos have mass is exciting. The Standard Model (SM) cannot accommodate non-zero neutrino mass terms without some modification. We must either introduce right-handed neutrinos (to generate Dirac mass terms) or allow neutrinos to be their own antiparticle (violating lepton number conservation, and allowing Majorana mass terms). Hence *the physics of neutrino masses is physics beyond the Standard Model*. Although we do not know the neutrino mass spectrum, we do know that the masses, and the associated mass-splittings, are tiny compared to the masses of any other fundamental fermion. This suggests that the physics responsible for neutrino mass will include new components radically different from those of the SM. Furthermore, although we do not have complete knowledge of the mixing between different neutrino flavors, we do know that it is qualitatively very different from the corresponding mixing between different quark flavors. The observed difference necessarily constrains our ideas about the underlying relationship between quarks and leptons, and hence models of quark and lepton unification in general, and Grand Unified Theories (GUTs) in particular. Note that in neutrino mass models the seesaw mechanism [4–8] provides a quantitative explanation for the observed small neutrino masses, which arise as a consequence of the existence of right-handed neutral leptons at the GUT-scale. Over the last few years, as our knowledge of the neutrino oscillation parameters

has improved, a previous generation of neutrino mass models has already been ruled out, and a new set of models has emerged specifically designed to accommodate the neutrino parameters. Further improvement in our knowledge of the oscillation parameters will necessarily reject many of these models, and presumably encourage the emergence of new ideas. Hence *neutrino physics is experimentally driven, and the experiments are already directing our ideas about what lies beyond the Standard Model*.

In addition to providing clues about physics beyond the SM, understanding neutrino properties is also important because neutrinos are the most common matter particles in the universe. In number, they exceed the constituents of ordinary matter (electrons, protons, neutrons) by a factor of ten billion. They probably account for at least as much energy in the universe as all the stars combined and, depending on their exact masses, might also account for a few percent of the so-called “dark matter”. In addition, neutrinos are important in stellar processes. There are 70 billion per second streaming through each square centimeter of the Earth from the Sun. Neutrinos govern the dynamics of supernovae, and hence the production of heavy elements in the universe. Furthermore, if there is CP violation in the neutrino sector, the physics of neutrinos in the early universe might ultimately be responsible for baryogenesis. *If we are to understand “why we are here” and the basic nature of the universe in which we live, we must understand the basic properties of the neutrino*.

Our desire to understand both the universe in which we live and physics beyond the SM provides a compelling case for an experimental program that can elucidate the neutrino mass spectrum, measure neutrino mixing, and test the three-flavor mixing framework. To identify the best ways to address the most important open neutrino questions, and to determine an effective, fruitful U.S. role within a global experimental neutrino program, the American Physical Society’s Divisions of Nuclear Physics and Particles and Fields, together with the Divisions of Astrophysics and the Physics of Beams, have recently conducted a “Study on the Physics of Neutri-

nos”. This study recommended [9] “... as a high priority, a comprehensive U.S. program to complete our understanding of neutrino mixing, to determine the character of the neutrino mass spectrum, and to search for CP violation among neutrinos”, and identified, as a key ingredient of the future program, “A proton driver in the megawatt class or above and neutrino superbeam with an appropriate very large detector capable of observing CP violation and measuring the neutrino mass-squared differences and mixing parameters with high precision.” The proposed Fermilab Proton Driver would, together with a suitable new detector, fulfill this need by providing a 2 megawatt proton beam at Main Injector (MI) energies for the future NuMI [10] program.

The NuMI beam is unique. It is the only neutrino beam that has an appropriate energy and a sufficiently long baseline to produce, due to matter effects, significant changes in the effective oscillation parameters. These matter effects can be exploited to determine the pattern of neutrino masses. Furthermore, when combined with measurements from the much-shorter-baseline T2K experiment [11] being built in Japan, an appropriate NuMI-based experiment could exploit matter effects to achieve a greatly enhanced sensitivity to CP violation in the neutrino sector.

Although neutrino oscillations provide the primary motivation for interest in the Fermilab Proton Driver, the participation in recent proton driver physics workshops has been broader than the neutrino physics community. Note that intense neutrino, muon, pion, kaon, neutron, and antiproton beams at the Fermilab Proton Driver would offer great flexibility and could support a diverse program of experiments of interest to particle physicists, nuclear physicists, and nuclear-astrophysicists. In particular, as the Large Hadron Collider (LHC) and the ILC begin to probe the energy frontier, a new round of precision flavor physics experiments at the Fermilab Proton Driver would provide information that is complementary to the LHC and ILC data by indirectly probing high mass scales through radiative corrections. This would help to elucidate the nature of any new physics that is discovered at the energy frontier.

### 3. OSCILLATION MEASUREMENTS

To understand the neutrino oscillation physics reach at the Fermilab Proton Driver we first introduce the three-flavor mixing parameters, and then discuss event rates and discovery potential.

#### 3.1. Three-Flavor Mixing Parameters

There are three known neutrino flavor eigenstates  $\nu_\alpha = (\nu_e, \nu_\mu, \nu_\tau)$ . Since transitions have been observed between the flavor eigenstates we now know that neutrinos have non-zero masses, and that there is mixing between the flavor eigenstates. The mass eigenstates  $\nu_i = (\nu_1, \nu_2, \nu_3)$  with masses  $m_i = (m_1, m_2, m_3)$  are related to the flavor eigenstates by a  $3 \times 3$  unitary mixing matrix  $U^\nu$  [12],

$$|\nu_\alpha\rangle = \sum_i (U_{\alpha i}^\nu)^* |\nu_i\rangle \quad (1)$$

Four numbers are needed to specify all of the matrix elements, namely three mixing angles ( $\theta_{12}, \theta_{23}, \theta_{13}$ ) and one complex phase ( $\delta$ ). In terms of these parameters:  $U^\nu =$

$$\begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} & c_{23}c_{12} & c_{13}s_{23} \\ -s_{13}s_{23}c_{12}e^{i\delta} & -s_{13}s_{23}s_{12}e^{i\delta} & c_{13}c_{23} \\ s_{23}s_{12} & -s_{23}c_{12} & c_{13}c_{23} \\ -s_{13}c_{23}c_{12}e^{i\delta} & -s_{13}c_{23}s_{12}e^{i\delta} & c_{13}s_{23} \end{pmatrix} \quad (2)$$

where  $c_{jk} \equiv \cos\theta_{jk}$  and  $s_{jk} \equiv \sin\theta_{jk}$ . Neutrino oscillation measurements have already provided some knowledge of  $U^\nu$ , which is approximately given by:

$$U^\nu = \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \quad (3)$$

We have limited knowledge of the (1,3)-element of the mixing matrix. This matrix element is parametrized by  $s_{13}e^{-i\delta}$ . We have only an upper limit on  $\theta_{13}$  and no knowledge of  $\delta$ . Note that  $\theta_{13}$  and  $\delta$  are particularly important because if  $\theta_{13}$  and  $\sin\delta$  are non-zero there will be CP violation in the neutrino sector.

Neutrino oscillations are driven by the splittings between the neutrino mass eigenstates. It

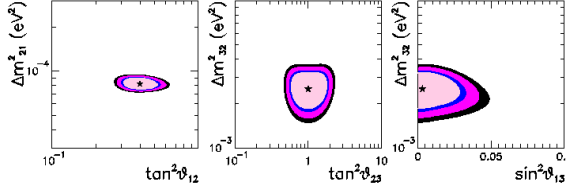


Figure 2. Current experimental constraints on the three mixing angles  $\theta_{12}$ ,  $\theta_{23}$ , and  $\theta_{13}$  and on the two mass-squared differences  $\Delta m_{12}^2$  and  $\Delta m_{23}^2$ . The star indicates the most likely solution. Figure taken from [9].

is useful to define the differences between the squares of the masses of the mass eigenstates  $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$ . The probability that a neutrino of energy  $E$  and initial flavor  $\alpha$  will “oscillate” into a neutrino of flavor  $\beta$  is given by  $P_{\alpha\beta} \equiv P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \exp(-i\mathcal{H}t) | \nu_\alpha \rangle|^2$ , which in vacuum is given by

$$P_{\alpha\beta} = \sum_{j=1}^3 \sum_{k=1}^3 U_{\alpha j} U_{\alpha k}^* U_{\beta j}^* U_{\beta k} \exp\left(-i \frac{\Delta m_{kj}^2}{2E} t\right) \quad (4)$$

If neutrinos of energy  $E$  travel a distance  $L$  then a non-zero  $\Delta m_{ij}^2$  will result in neutrino flavor oscillations that have maxima at given values of  $L/E$ , and oscillation amplitudes that are determined by the matrix elements  $U_{\alpha i}^\nu$ , and hence by  $\theta_{12}, \theta_{23}, \theta_{13}$ , and  $\delta$ .

Our present knowledge of the neutrino mass splittings and mixing matrix, has been obtained from atmospheric [13, 14], solar [15–20], reactor [21–23], and accelerator-based [24] neutrino experiments, and is summarized in Fig. 2. The solar-neutrino experiments and the reactor experiment KamLAND probe values of  $L/E$  that are sensitive to  $\Delta m_{21}^2$ , and the mixing angle  $\theta_{12}$ . Our knowledge of these parameters is shown in the left panel of Fig. 2. The atmospheric-neutrino experiments and the accelerator based experiment K2K probe values of  $L/E$  that are sensitive to  $\Delta m_{32}^2$ , and the mixing angle  $\theta_{23}$ . Our knowledge of these parameters is shown in the central panel of Fig. 2. Searches for  $\nu_\mu \leftrightarrow \nu_e$  transitions with

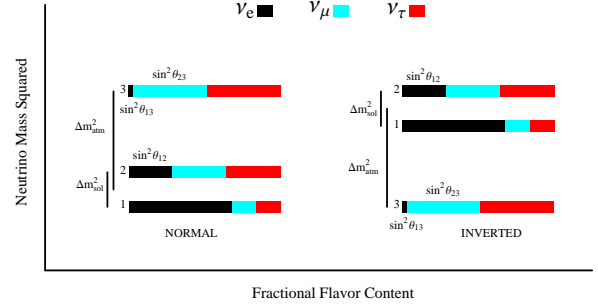


Figure 3. The two possible arrangements of the masses of the three known neutrinos, based on neutrino oscillation measurements. The spectrum on the left corresponds to the *Normal Hierarchy* and has  $\Delta m_{32}^2 > 0$ . The spectrum on the right corresponds to the *Inverted Hierarchy* and has  $\Delta m_{32}^2 < 0$ . The  $\nu_e$  fraction of each mass eigenstate is indicated by the black solid region. The  $\nu_\mu$  and  $\nu_\tau$  fractions are indicated by the blue (red) regions respectively. The  $\nu_e$  fraction in the mass eigenstate labeled “3” has been set to the CHOOZ bound. Figure from Ref. [38].

values of  $L/E$  corresponding to the atmospheric-neutrino scale are sensitive to the third mixing angle  $\theta_{13}$ . To date these searches have not observed this transition, and hence we have only an upper limit on  $\theta_{13}$ , which comes predominantly from the CHOOZ reactor experiment [21], and is shown in the right panel of Fig. 2.

The mixing angles tell us about the flavor content of the neutrino mass eigenstates. Our knowledge of the  $\Delta m_{ij}^2$  and the flavor content of the mass eigenstates is summarized in Fig. 3. Note that there are two possible patterns of neutrino mass. This is because the neutrino oscillation experiments to date have been sensitive to the magnitude of  $\Delta m_{32}^2$ , but not its sign. The neutrino spectrum shown on the left in Fig. 3 is called the *Normal Mass Hierarchy* and corresponds to  $\Delta m_{32}^2 > 0$ . The neutrino spectrum shown on the right is called the *Inverted Mass Hierarchy* and

Table 1

Signal and background  $\nu_\mu \rightarrow \nu_e$  event rates for values of  $\theta_{13}$  that are just below the present upper limit and an order of magnitude below the upper limit. The rates are for the normal mass hierarchy and  $\delta = 0$ . The numbers for each experiment correspond to 5 years of running with the nominal beam intensities.

Experiment	Signal $\sin^2 2\theta_{13} = 0.1$	Signal $\sin^2 2\theta_{13} = 0.01$	Background
MINOS	49.1	6.7	108
ICARUS	31.8	4.5	69.1
OPERA	11.2	1.6	28.3
T2K	132	16.9	22.7
NO $\nu$ A	186	23.0	19.7
NO $\nu$ A+FPD	716	88.6	75.6
NuFACT (neutrinos)	29752	4071	44.9
NuFACT (antineutrinos)	7737	1116	82.0

From the calculations of W. Winter, based on the Globes program [28].

Table 2

Signal and background  $\nu_\mu \rightarrow \nu_e$  event rates for  $\theta_{13}$  just below the present upper limit ( $\sin^2 2\theta_{13} = 0.1$ ). The rates are for the normal and inverted mass hierarchies with  $\delta = 0$  (no CP violation) and  $\delta = \pi/2$  (maximal CP violation). The numbers for each experiment correspond to 5 years of running with the nominal beam intensities.

Experiment	Normal $\delta = 0$	Normal $\delta = \pi/2$	Inverted $\delta = 0$	Inverted $\delta = \pi/2$	Back- ground
T2K	132	96	102	83	22.7
NO $\nu$ A	186	138	111	85	19.7
NO $\nu$ A+FPD	716	531	430	326	75.6
NuFACT ( $\nu$ )	29752	27449	13060	17562	44.9
NuFACT ( $\bar{\nu}$ )	7737	5942	9336	10251	82.0

From the calculations of W. Winter, based on the Globes program [28].

corresponds to  $\Delta m_{32}^2 < 0$ . The reason we don't know the sign of  $\Delta m_{32}^2$ , and hence the neutrino mass hierarchy, is that neutrino oscillations in vacuum depend only on the magnitude of  $\Delta m_{32}^2$ . However, in matter the effective parameters describing neutrino transitions involving electron-type neutrinos are modified [25] in a way that is sensitive to the sign of  $\Delta m_{32}^2$ . An experiment with a sufficiently long baseline in matter and an appropriate  $L/E$  can therefore determine the neutrino mass hierarchy.

Finally, it should be noted that there is a possible complication to the simple three-flavor

neutrino oscillation picture. The LSND [26] experiment has reported evidence for muon anti-neutrino to electron anti-neutrino transitions for values of  $L/E$  which are two orders of magnitude smaller than the corresponding values observed for atmospheric neutrinos. The associated transition probability is very small, of the order of 0.3%. If this result is confirmed by the Mini-BooNE [32] experiment, it will require a third characteristic  $L/E$  range for neutrino flavor transitions. Since each  $L/E$  range implies a different mass-splitting between the participating neutrino mass eigenstates, confirmation of the LSND result

would require more than three mass eigenstates. This would be an exciting and radical development. Independent of whether the LSND result is confirmed or not, it is important that the future global neutrino oscillation program is able to make further tests of the three-flavor oscillation framework.

### 3.2. Event Rates

To obtain sufficient statistical sensitivity to determine the pattern of neutrino masses and search for CP violation over a large region of parameter-space will require a new detector with a fiducial mass of tens of kilotons and a neutrino beam with the highest practical intensity. To illustrate this, consider the NuMI event rates in the far detector. The present NuMI primary proton beam intensity is roughly  $10^{13}$  protons per second at 120 GeV, which corresponds to 0.2 megawatts on target. These protons are used to make a secondary charged pion beam, which is focussed into a parallel beam using magnetic horns. The pion beam is then allowed to decay whilst propagating down a long decay channel, to create a tertiary beam of muon-neutrinos. At the far detector, 735 km downstream of the target, there are  $10^{-5}$  neutrino interactions in a 1 kt detector for every  $10^{13}$  protons on target. Note that we are interested in  $\nu_\mu \rightarrow \nu_e$  oscillations, and that the present upper limit on  $\theta_{13}$  implies that the relevant oscillation amplitude is at most  $\sim 5\%$ . Putting these numbers together one quickly concludes that we will need proton beam powers of one or a few megawatts together with detectors of a few times 10 kt.

To be explicit, the expected  $\nu_\mu \rightarrow \nu_e$  event rates for future experiments are listed in Table 1 for two values of  $\theta_{13}$ . Note that signal and background rates for the T2K and NO $\nu$ A [27] experiments are comparable and will at best (for the most favorable  $\theta_{13}$ ) yield data samples of only  $\sim 100$  events. This may be sufficient to pin down  $\theta_{13}$ , is at best barely sufficient to make the first determination of the mass hierarchy, and is inadequate to search for CP violation or make precision measurements of the interesting parameters. The Fermilab Proton Driver, together with NO $\nu$ A, does significantly better.

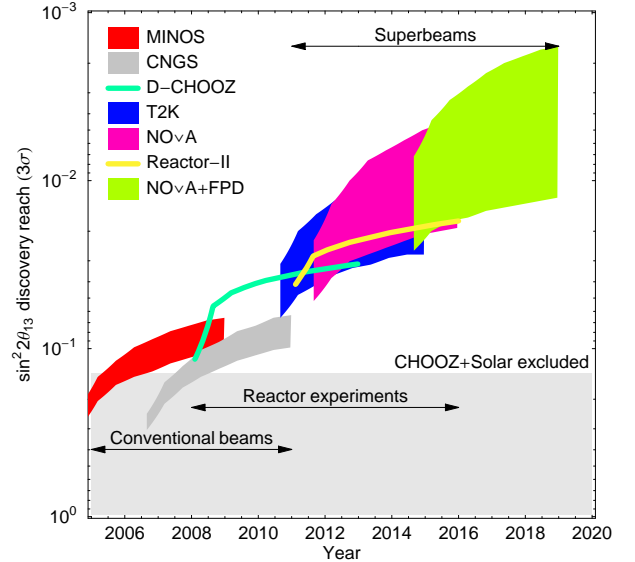


Figure 4. Anticipated evolution of the  $\theta_{13}$  discovery reach. The  $3\sigma$  sensitivities for the observation of a non-zero  $\sin^2 2\theta_{13}$ . The bands reflect the dependence on the CP phase  $\delta$ . The calculations are for a normal mass hierarchy and are based on the simulations in [28, 29] and include statistical and systematic uncertainties and parameter correlations. All experiments are operated with neutrino running only. The starting times of the experiments correspond to those stated in the respective LOIs. ReactorII and FPD refer, respectively, to a second generation reactor experiment and to the Fermilab Proton Driver.

Although the signal and background rates for T2K and NO $\nu$ A are comparable, the two experiments are complementary in the way they are sensitive to the oscillation parameters. This is illustrated in Table 2 which compares event rates for the two mass hierarchies and for CP conserving and CP violating values of  $\delta$ . With the Proton Driver, there is a statistically significant dependence of event rates on both the mass hierarchy and the phase  $\delta$ . In contrast, the T2K rates are

not as sensitive to the mass hierarchy. Hence the combination of both experiments provides a way to disentangle the parameters.

### 3.3. Discovery Potential

To complete our knowledge of the neutrino mixing matrix and the pattern of neutrino masses we must measure  $\theta_{13}$  and  $\delta$ , determine the sign of  $\Delta m_{32}^2$ , and test the three-flavor mixing framework. The initial goal for a Fermilab Proton Driver experiment will be to make these measurements. How far this physics program can be pursued will depend upon the magnitude of the unknown mixing angle  $\theta_{13}$ .

The anticipated evolution of the  $\sin^2 2\theta_{13}$  discovery reach of the global neutrino oscillation program is illustrated in Fig. 4. The sensitivity is expected to improve by about an order of magnitude over the next decade. This progress is likely to be accomplished in several steps, each yielding a factor of a few increased sensitivity. During this first decade the Fermilab program will have contributed to the improving global sensitivity with MINOS, followed by NO $\nu$ A. MINOS is the on-ramp for the US long-baseline neutrino oscillation program. NO $\nu$ A would be the next step. Note that we assume that NO $\nu$ A starts taking data with the existing beamline before the Proton Driver era. The Proton Driver would take NO $\nu$ A into the fast lane of the global program. Also note that the accelerator based and reactor based experiments are complementary. In particular, the reactor experiments make disappearance measurements, limited by systematic uncertainties. The NO $\nu$ A experiment is an appearance experiment, limited by statistical uncertainties, and probes regions of parameter space beyond the reach of the proposed reactor experiments.

Although we don't know the value of  $\theta_{13}$  we have no reason to suspect that it is very small. Hence, any of the experiments on the trajectory show in Fig. 4 might establish a finite value for  $\theta_{13}$ . At this point the focus of the experimental program will change from establishing the magnitude of  $\theta_{13}$  to measuring the mass hierarchy and searching for CP violation. Independent of the value of  $\theta_{13}$  the initial Fermilab Proton Driver long-baseline neutrino experiment (NO $\nu$ A+FPD)

would be expected to make an important contribution to the global oscillation program. If  $\theta_{13}$  is very small NO $\nu$ A+FPD would provide the most stringent limit on this important parameter, and prepare the way for a neutrino factory [30]. If  $\theta_{13}$  is sufficiently large, NO $\nu$ A+FPD would be expected to measure its value, perhaps determine the mass hierarchy, and prepare the way for a sensitive search for CP violation. The evolution of the Fermilab Proton Driver physics program beyond the initial experiments will depend on the value of  $\theta_{13}$  and on what other neutrino experiments are built elsewhere in the world. Hence, in considering the long-term evolution of the Fermilab Proton Driver program we must take into account the uncertainty on the magnitude of  $\theta_{13}$  and consider how the global program might evolve.

The experiments needed to determine the mass hierarchy and discover (or place stringent limits on) CP violation will depend upon both  $\theta_{13}$  and on  $\delta$ . The fractions of all possible values of  $\delta$  for which a discovery can be made are shown as a function of  $\sin^2 2\theta_{13}$  in Fig. 5 for various experiments. The left panel shows the potential for determining the mass hierarchy and the right panel for making a first observation of CP violation. Note that without a megawatt-class proton source none of the future experiments will be able to make a sensitive search for CP violation. The NO $\nu$ A experiment (labelled NUE in the figure) can make a first determination of the mass hierarchy, but only over a very limited region of parameter space. The Fermilab Proton Driver would significantly improve the prospects for determining the mass hierarchy, and if  $\theta_{13}$  is relatively large, would enable the first sensitive search for CP violation. Combining NO $\nu$ A and T2K results would enable further progress if the T2K experiment was upgraded to achieve a factor of a few larger data samples (T2K $^*$ ). The mass hierarchy could then be determined independent of  $\delta$  provided  $\sin^2 2\theta_{13}$  exceeds about 0.04. Smaller values of  $\theta_{13}$  will motivate a much more ambitious experimental program which will probably include a Neutrino Factory. Larger values of  $\theta_{13}$  will still motivate a more ambitious experimental program focussed on the precision measure-

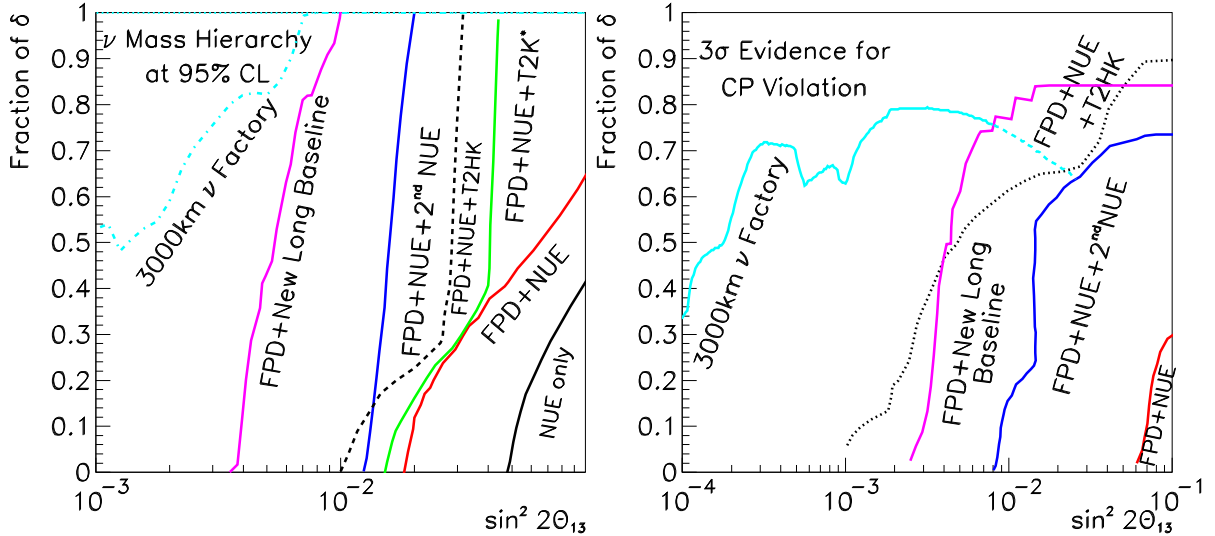


Figure 5. Regions of parameter space where the mass hierarchy (left) and CP violation (right) can be observed at 95% CL and at  $3\sigma$ , respectively. The label NUE refers to the NO $\nu$ A experiment, and FPD to the Fermilab Proton Driver. T2K\* refers to an upgraded T2K experiment with a 4 megawatt primary beam.

ments that would put the presently viable theoretical models under pressure. The second generation of Fermilab Proton Driver experiments might, in this case, include a second off-axis detector and/or a new longer-baseline beam. Note that, since a Proton Driver can be used to drive a Neutrino Factory, the Fermilab Proton Driver offers great flexibility for a second generation program independent of the value of  $\theta_{13}$ .

#### 4. OTHER PHYSICS

In the past, high precision measurements at low energies have complemented the experimental program at the energy frontier. These low energy experiments not only probe mass scales that are often beyond the reach of colliders, but also provide complementary information at mass scales within reach of the energy frontier experiments. Examples of low energy experiments that have played an important role in this way are muon ( $g - 2$ ) measurements, searches for muon

and kaon decays beyond those predicted by the SM, and other measurements of rare muon and kaon processes. A summary of the sensitivity achieved by a selection of these experiments is given in Fig. 6. It seems likely that these types of experiment will continue to have a critical role as the energy frontier moves into the LHC and ILC era. In particular, if the LHC and/or ILC discover new physics beyond the SM, the measurement of quantum corrections that manifest themselves in low energy experiments would be expected to help elucidate the nature of the new physics. If no new physics is discovered at the LHC then precision low energy experiments may provide the only practical way of advancing the energy frontier beyond the LHC in the foreseeable future.

In addition to complementing collider experiments at the energy frontier, intense neutrino, muon, pion, kaon, neutron, and antiproton beams at the Fermilab Proton Driver could also sup-

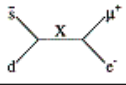
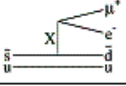
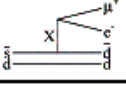
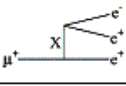
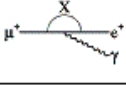
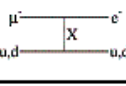
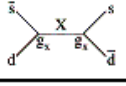
$\Delta G = 0 \text{ or } 2$	Experimental Result (90% CL)	M or $\Delta M$ Limit
	$B(K_L^0 \rightarrow \mu^+ e^-) < 4.7 \times 10^{-12}$	150 TeV/c <sup>2</sup>
	$B(K^+ \rightarrow \pi^+ \mu^+ e^-) < 4 \times 10^{-11}$	31 TeV/c <sup>2</sup>
	$B(K_L^0 \rightarrow \pi^0 \mu^+ e^-) < 3.2 \times 10^{-10}$	37 TeV/c <sup>2</sup>
<b><math>\Delta G = 1</math></b>		
	$B(\mu \rightarrow eee) < 1 \times 10^{-12}$	86 TeV/c <sup>2</sup>
	$B(\mu^+ \rightarrow e^+ \gamma) < 1.2 \times 10^{-11}$	21 TeV/c <sup>2</sup>
	$\frac{\Gamma(\mu^- A \rightarrow e^- A)}{\Gamma(\mu^- A \rightarrow \nu A')} < 6.1 \times 10^{-13}$	365 TeV/c <sup>2</sup>
<b><math>\Delta G = \pm 2</math></b>		
	$\Delta M_K < 3.5 \times 10^{-12} \text{ MeV/c}^2$	400 TeV/c <sup>2</sup>

Figure 6. Current limits on Lepton Flavor Violating processes and the mass scales probed by each process. The upper box is for kaon decays, which involve a change of both quark flavor and lepton flavor. The bottom box is for muon decays, which involve only lepton flavor change. The lower limit on the mass scale is calculated assuming the electroweak coupling strength.

port a diverse program of experiments of interest to particle physicists, nuclear physicists, and nuclear-astrophysicists, and offer great flexibility for the future program. Of the various possibilities that have been considered, neutrino scattering physics and the potential physics program that could be pursued with an intense low energy muon source offer particularly attractive options that would complement, and could be run in parallel with, the neutrino oscillation program.

#### 4.1. Neutrino Scattering

While neutrino oscillation experiments probe the physics of neutrino masses and mixing, neutrino scattering experiments probe the interactions of neutrinos with ordinary matter, and enable a search for exotic neutrino properties. A complete knowledge of the role of neutrinos in the Universe in which we live requires a detailed knowledge of neutrino masses, mixing, and interactions.

Our present knowledge of the neutrino and

anti-neutrino scattering cross sections in matter is limited. The next generation of approved neutrino scattering experiments, including MINER $\nu$ A [31] in the NuMI beamline and MiniBooNE [32] using neutrinos from the Fermilab Booster, are expected to greatly improve our knowledge. In particular, within the next few years we anticipate that precise measurements will be made of neutrino scattering on nuclear targets. However, we will still lack precise measurements of:

- Anti-Neutrino scattering on nuclear targets.
- Neutrino and anti-neutrino scattering on nucleon (hydrogen and deuterium) targets.
- Neutrino-electron scattering.

The anti-neutrino rates per primary proton on target are, depending on energy, a factor of 3-5 less than the neutrino rates. The interaction rates on nucleon targets are an order of magnitude less than the corresponding rates on nuclear targets, and the cross-section for neutrino-electron scattering is considerably smaller than that on nucleons. Hence, beyond the presently approved program, a factor of 10-100 increase in data rates will be required to complete the neutrino and anti-neutrino scattering measurements. The physics topics that could be pursued with a neutrino scattering program at the Fermilab Proton Driver include (i) a study of neutrino-electron scattering and a search for a neutrino magnetic moment, (ii) measurements of parton distribution functions, particularly at large  $x$ , (iii) a study of generalized parton distribution functions to determine the partonic spatial distributions as a function of longitudinal momenta, (iv) measurements of the strange-quark content and spin structure of the nucleon, (v) a measurement of the nuclear weak form factor to better understand the  $G_E$  and  $G_M$  measurements at JLab [33], (vi) studies of duality and resonance production to better understand the transition between the domain where partons are the appropriate degrees of freedom to the domain where baryons and mesons provide the appropriate description, and (vii) strange particle production studies to test theoretical models [34] of NC induced strange particle production.

In addition to being of interest in their own right, neutrino scattering experiments will also play a key role in allowing future precision oscillation experiments to reach their ultimate sensitivity. To obtain the most precise value of  $\Delta m_{32}^2$  (which is eventually required to extract mixing angles and the CP-violating phase) we must better understand and quantify the nuclear processes interposed between the interaction of an incoming neutrino and measurement of outgoing particles in the detector. Extracting mixing parameters such as  $\theta_{13}$ , and ultimately the neutrino mass hierarchy and CP phase, also requires much better understanding of the neutral current resonant and coherent cross-sections that contribute to the background. The precision measurement of nuclear effects and exclusive cross-sections will provide the necessary foundation for the study of neutrino oscillations with high-intensity beams at the Fermilab Proton Driver.

#### 4.2. Muon Physics

Solar-, atmospheric-, and reactor-neutrino experiments have established Lepton Flavor Violation (LFV) in the neutrino sector, which suggests the existence of LFV processes at high mass scales. Depending on its nature, this new physics might also produce observable effects in rare muon processes. Furthermore, CP violation in the charged lepton sector, revealed for example by the observation of a finite muon Electric Dipole Moment (EDM), might be part of a broader baryogenesis via leptogenesis picture. Hence, the neutrino oscillation discovery enhances the motivation for a continuing program of precision muon experiments. In addition, the expectation that there is new physics at the TeV scale also motivates a new round of precision muon experiments. LFV muon decays and the muon anomalous magnetic moment  $a_\mu = (g - 2)/2$  and EDM are sensitive probes of new dynamics at the TeV scale. In general, with sufficient sensitivity, these experiments would help elucidate the nature of new physics observed at the LHC and ILC.

Low energy high precision muon experiments require high intensity beams. Since most of the 8 GeV Fermilab Proton Driver beam from the SC linac would not be used to fill the MI, it

Table 3

A comparison of the present or near future sensitivities for some representative muon experiments with the sensitivities that are in principle attainable with a Fermilab Proton Driver.

Measurement	Sensitivity	
	Present or Near Future	Fermilab Proton Driver
EDM $d_\mu$	$< 3.7 \times 10^{-19}$ e-cm	$< 10^{-24} - 10^{-26}$ e-cm
$(g - 2) \sigma(a_\mu)$	0.2 – 0.5 ppm	0.02 ppm
BR( $\mu \rightarrow e\gamma$ )	$\sim 10^{-14}$	$\sim 10^{-16}$
$\mu A \rightarrow eA$ Ratio	$\sim 10^{-17}$	$\sim 10^{-19}$

would be available to drive a high intensity muon source. In addition to high intensity, precision muon experiments also require an appropriate bunch structure, which varies with experiment. In the post-collider period it might be possible to utilize the Recycler Ring to repackage the 8 GeV proton beam, yielding a bunch structure optimized for each experiment. The combination of Proton Driver plus Recycler Ring would provide the front-end for a unique muon source with intensity and flexibility that exceed any existing facility.

The Recycler is an 8 GeV storage ring in the MI tunnel that can run at the same time as the MI. The beam from the Fermilab Proton Driver SC linac that is not used to fill the MI could be used to fill the Recycler Ring approximately ten times per second. The ring would then be emptied gradually in the 100 ms intervals between linac pulses. Extraction could be continuous or in bursts. For example, the Recycler Ring could be loaded with one linac pulse of  $1.5 \times 10^{14}$  protons every 100 ms, with one missing pulse every 1.5 seconds for the 120 GeV MI program. This provides  $\sim 1.4 \times 10^{22}$  protons at 8 GeV per operational year ( $10^7$  seconds). In the Recycler each pulse of  $1.5 \times 10^{14}$  protons can be chopped into 588 bunches of  $0.25 \times 10^{12}$  protons/bunch with a pulse width of 3 ns. A fast kicker would permit the extraction of one bunch at a time. The beam structure made possible by the Proton Driver linac and the Recycler Ring is perfect for  $\mu \rightarrow e$  conversion experiments, muon EDM searches and other muon experiments where a pulsed beam is required. Slow extraction from the Recycler Ring for  $\mu \rightarrow e\gamma$  and  $\mu \rightarrow 3e$  searches is also possible.

Using an 8 GeV primary proton beam together with a suitable target and solenoidal capture and decay channel, the calculated yield of low energy muons is  $\sim 0.2$  of each sign per incident proton [35]. With  $1.4 \times 10^{22}$  protons at 8 GeV per operational year (corresponding to  $\sim 2$  megawatts) this would yield  $\sim 3 \times 10^{21}$  muons per year. This muon flux greatly exceeds the flux required to make progress in a broad range of muon experiments. However, the muons at the end of the decay channel have low energy, a large momentum spread, and occupy a large transverse phase space. Without further manipulation their utilization will be very inefficient. The interface between the decay channel and each candidate experiment has yet to be designed. In Japan a Phase Rotated Intense Slow Muon Source (PRISM [36]) based on an FFAG ring that reduces the muon energy spread (phase rotates) is being designed. This phase rotation ring has a very large transverse acceptance ( $800\pi$  mm-mrad) and a momentum acceptance of  $\pm 30\%$  centered at 500 MeV/c. PRISM reduces the momentum and momentum spread to 68 MeV/c and  $\pm 1 - 2\%$  respectively. Hence, a PRISM-like ring downstream of the decay channel might accept a significant fraction of the muon spectrum and provide a relatively efficient way to use the available muon flux. Explicit design work must be done to verify this, but it should be noted that a muon selection system that utilizes only 1% of the muons available at the end of the decay channel will still produce an adequate muon flux for most of the desired cutting-edge experiments. Scaling from proposals for muon experiments at JPARC, and making some plausible assumptions about

the evolution of detector technology in the coming decade, the sensitivities that might be obtained at a Fermilab Proton Driver muon source are summarized in Table 3 for the leading desired experiments. Orders of magnitude improvements in sensitivity beyond those already achieved would be possible.

Finally, a new 8 GeV multi-megawatt Proton Driver at Fermilab, together with an appropriate target, pion capture system, decay channel, and phase rotation system could provide the first step toward a Neutrino Factory based on a muon storage ring. Hence, the development of a cutting edge muon program at the Fermilab Proton Driver is a particularly attractive complement to the long-term neutrino oscillation program.

## 5. CONCLUSIONS

In 2004 the Fermilab Long Range Planning Committee [37] identified a new high intensity Proton Driver as an attractive option for the future, primarily motivated by the recent exciting developments in neutrino physics. Over the last few months a physics study [2] has developed the physics case for the Fermilab Proton Driver that is described in this paper. The conclusions from the study are:

1. Independent of the value of the unknown mixing angle  $\theta_{13}$  an initial Fermilab Proton Driver long-baseline neutrino experiment will make a critical contribution to the global oscillation program.
2. If  $\theta_{13}$  is very small the initial Fermilab Proton Driver experiment will provide the most stringent limit on  $\theta_{13}$  and prepare the way for a neutrino factory. The expected  $\theta_{13}$  sensitivity exceeds that expected for reactor-based experiments, or any other accelerator-based experiments.
3. If  $\theta_{13}$  is sufficiently large the initial Fermilab Proton Driver experiment will precisely measure its value, perhaps determine the mass hierarchy, and prepare the way for a sensitive search for CP violation. The value of  $\theta_{13}$  will guide the further evolution of the Proton Driver neutrino program.

4. The Fermilab Proton Driver neutrino experiments will also make precision measurements of the other oscillation parameters, and conduct an extensive set of neutrino scattering measurements, some of which are important for the oscillation program. Note that the neutrino scattering measurements require the highest achievable intensities at both MI energies and at 8 GeV.

5. The Fermilab Proton Driver could also support a broad range of other experiments of interest to particle physicists, nuclear physicists, and nuclear astrophysicists. These experiments could exploit antiproton- and kaon-beams from the MI, or muon-, pion-, or neutron-beams from the 8 GeV linac. These “low energy” experiments would provide sensitivity to new physics at high mass scales which would be complementary to measurements at the LHC and beyond.

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